La référence de fréquence délivrée par le SYRTE

Paul-Eric Pottie
LNE-SYRTE

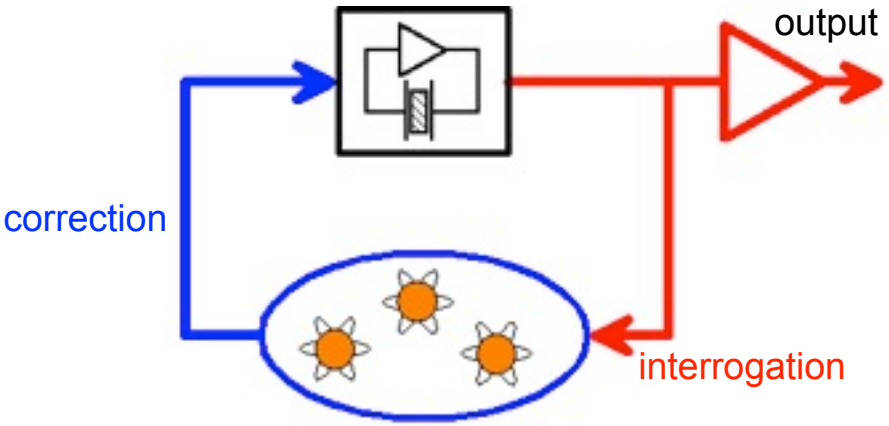
The frequency reference delivered by SYRTE

1. Frequency reference at SYRTE
2. The REFIMEVE+ Local Oscillator
3. The operational comb
4. Accuracy
5. What will you receive as signal ?

Atomic clocks

Let's start from basics…

macroscopic oscillator



$$\omega(t) = \omega_{ef} \times (1 + \varepsilon + y(t))$$

ε : relative frequency shift

accuracy: total uncertainty on ε

y(t) : relative frequency fluctuations

stability: Allan variance $\sigma_y^2(\tau)$

Statistical analysis of y(t)

τ = integration time

Clocks ensemble at SYRTE

Refimeve+

Macroscopic oscillators

Cryogenic Saphir Oscillator

H-maser

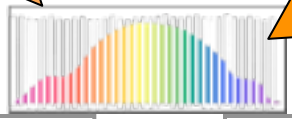
H

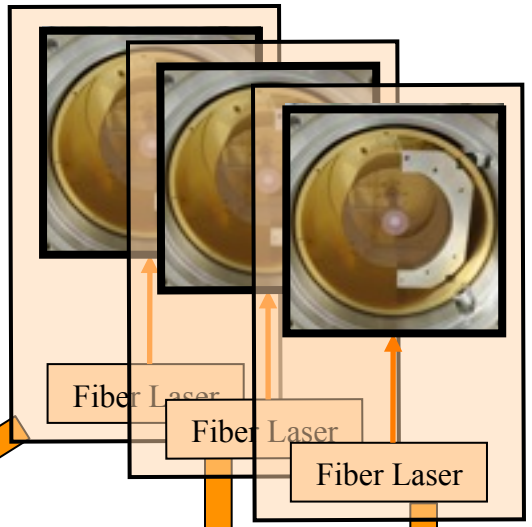
Phase loop
τ~1000 s

(CSO)

+1 GHz distribution

Frequency comb





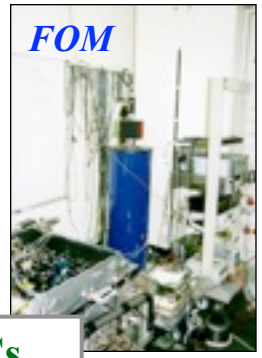
Ultra-stable Lasers

Atoms

Atomic fountains

FO1

FOM



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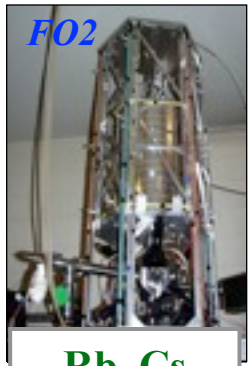


Cs

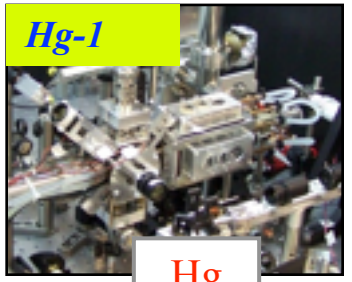
Rb, Cs

Optical lattice clocks

Sr1, Sr2

Sr

Hg-1



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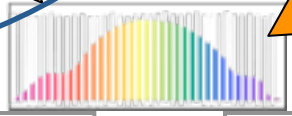

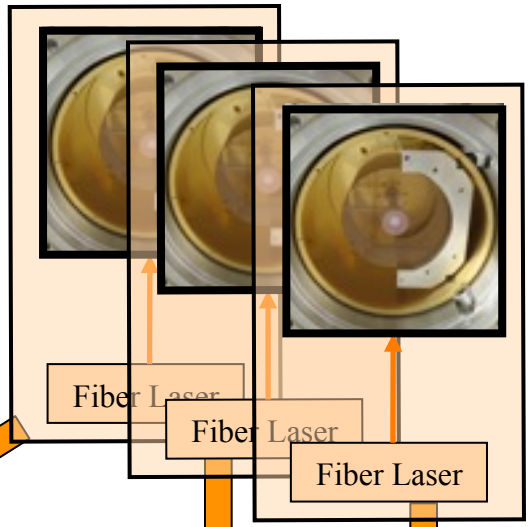

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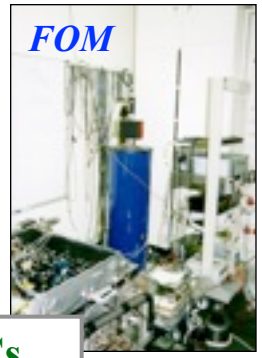

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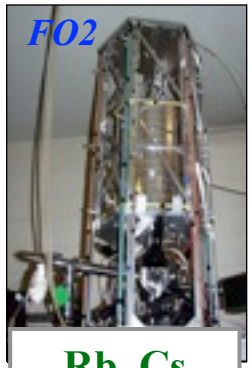

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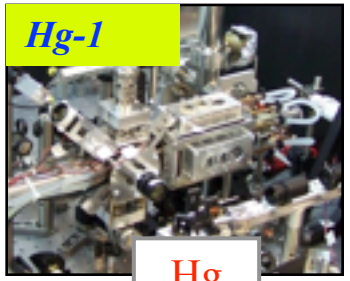

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Composite frequency reference

- Available ~24/7 since 2000 with LHe refills: 0.5 day every 25 days

- Benefits of an ultra stable reference
  - Best stability for atomic fountains: D. Chambon et al. , Rev. Sci. Instrum. 76, 094704 (2005)
  - 1.6×10^{-14} @1s => PFS comparison at 10^{-16}
  - Best stability for optical to microwave comparison

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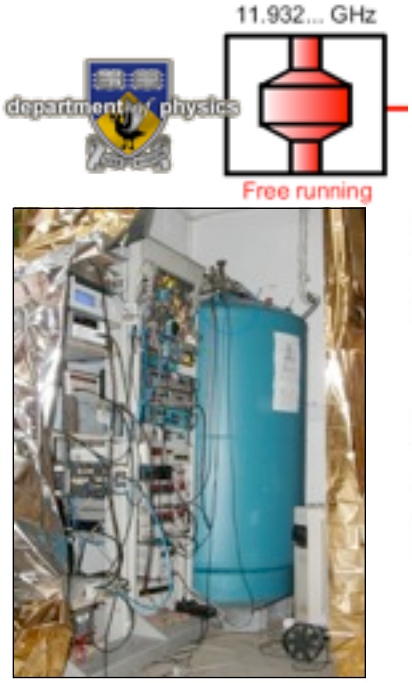

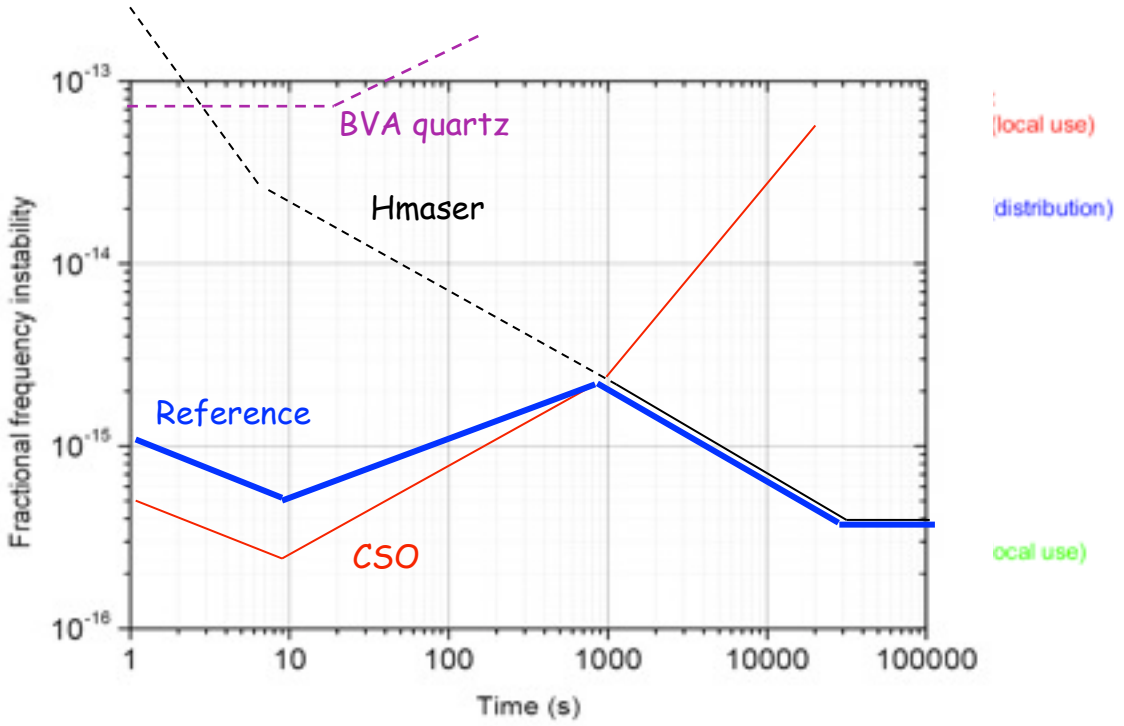

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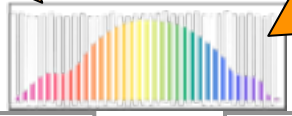

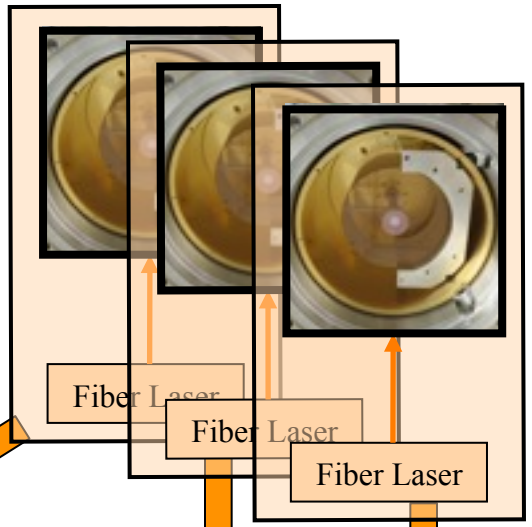

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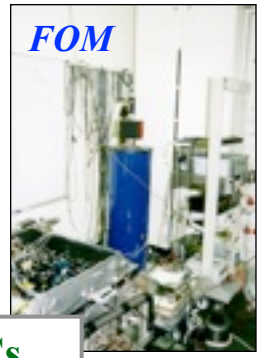

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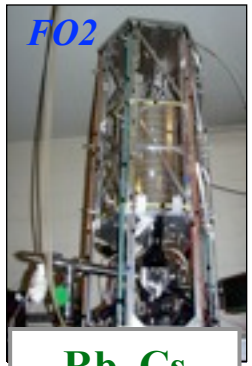

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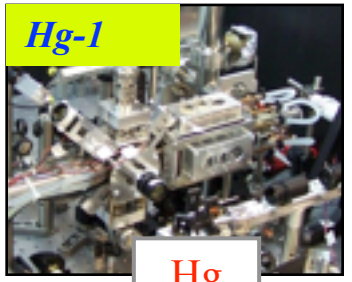

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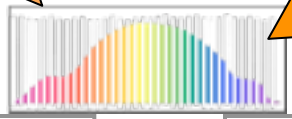

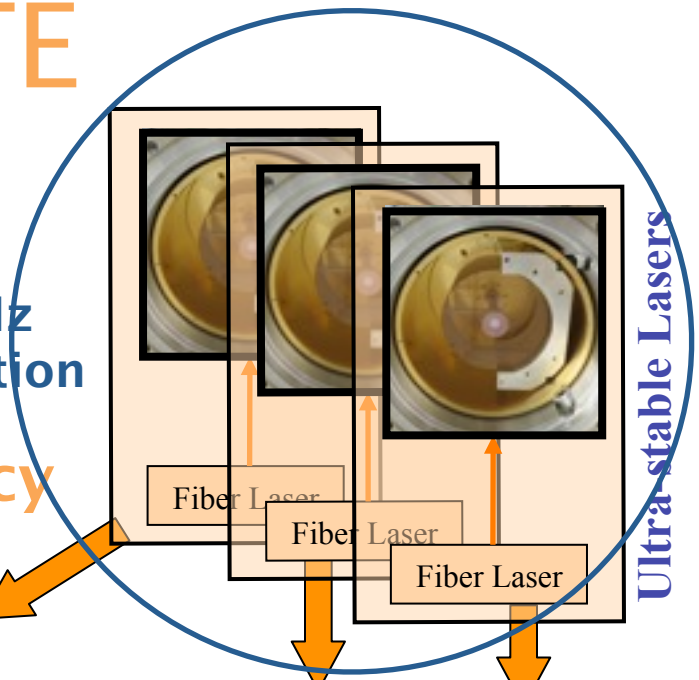

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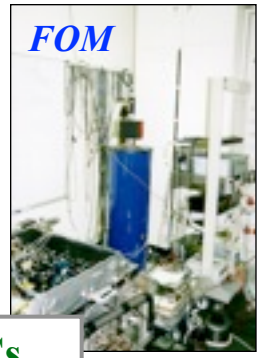

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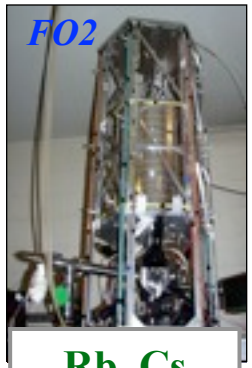

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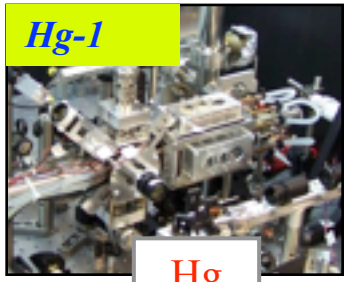

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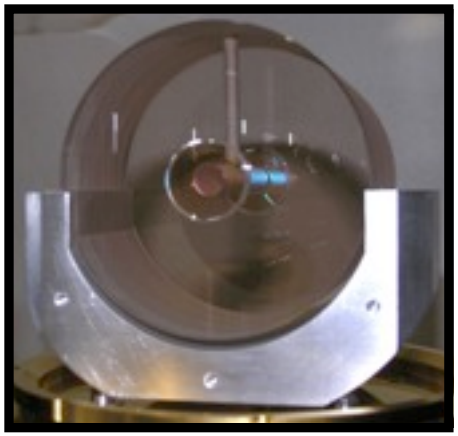
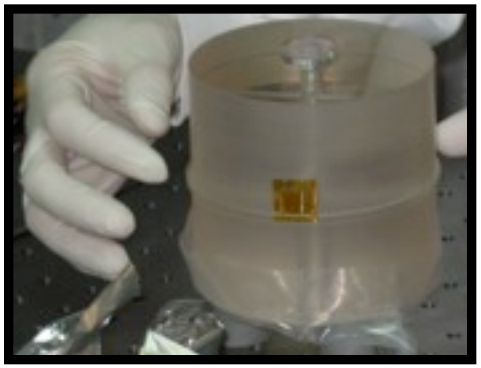
Ultra-stable lasers as local oscillators

Fiber lasers phase-locked with ultra-stable cavity

- Vacuum chamber (~10^{-8} mbar)
- Finesse : ~800 000
- Optimized shape for minimum sensitivity to acceleration
- ULE / FS, low thermal coefficient
- Thermal shields (<1nK residual) (Time cst ~ 4 days)
- Isolation platform





Ultra-stable lasers frequency stability

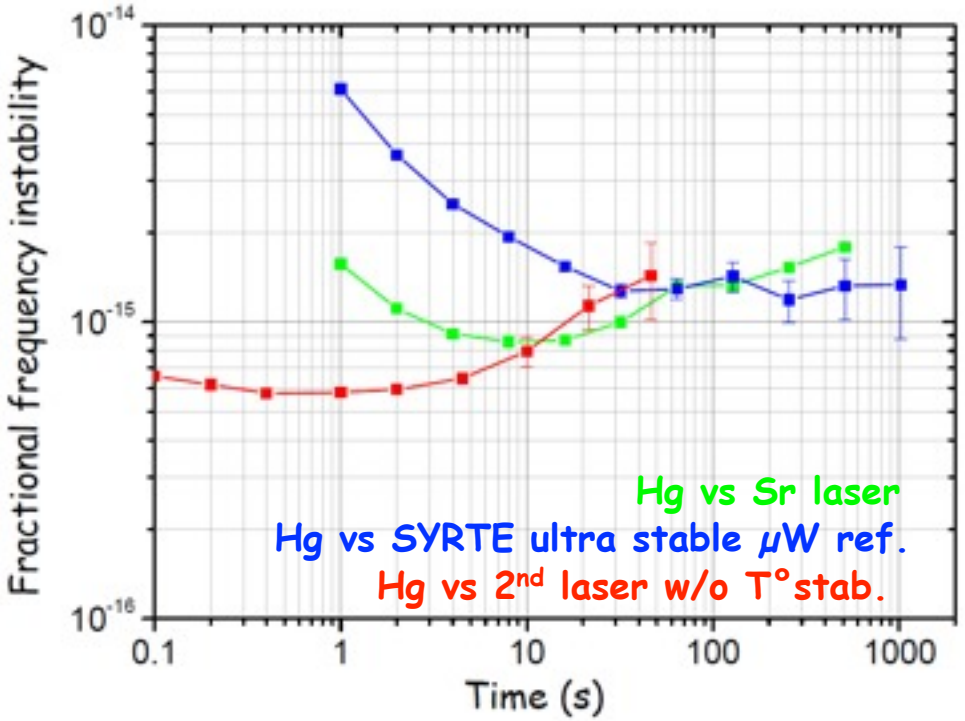
Refimeve+

Hg-laser case

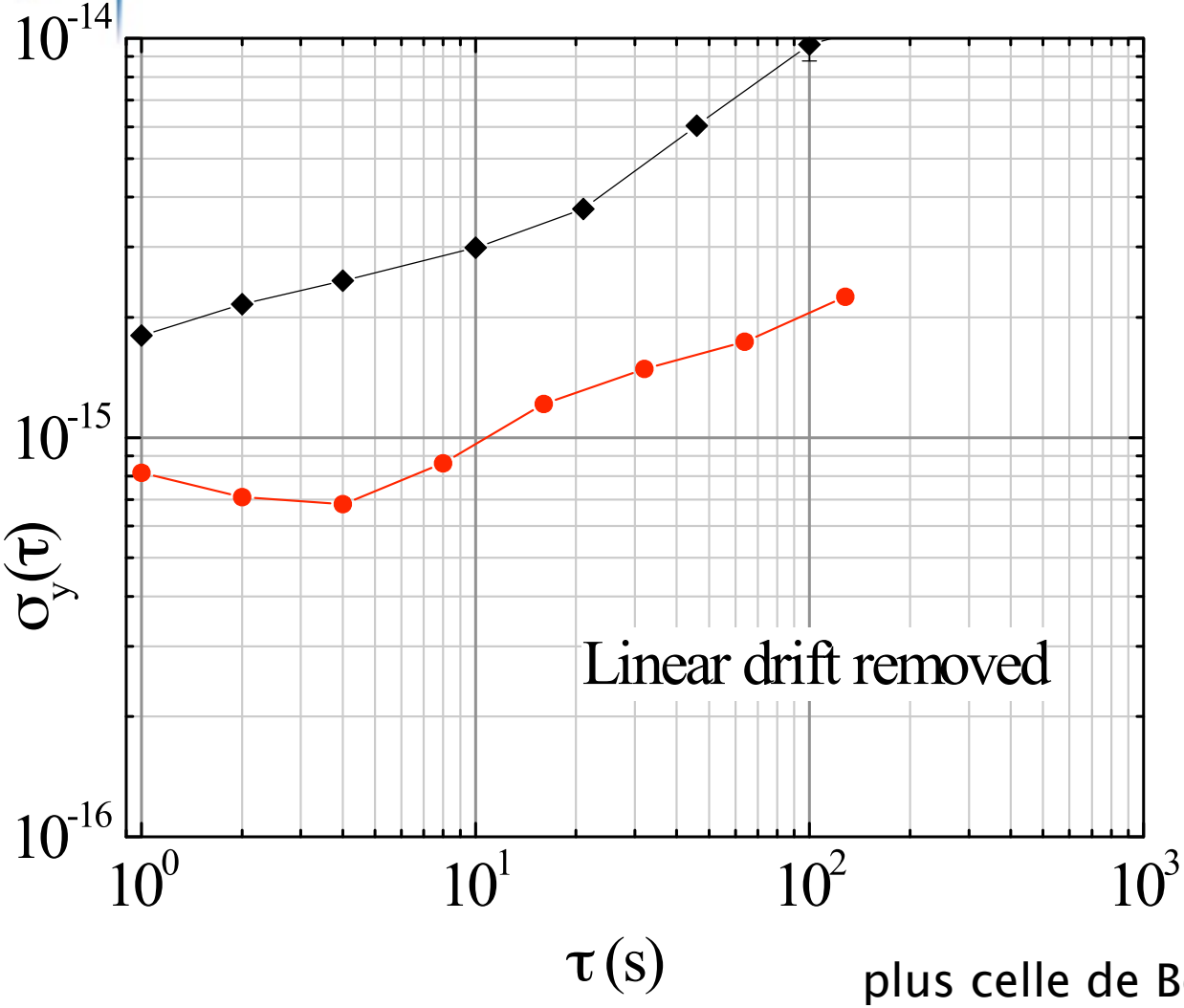
- Vertically mounted, low vibration sensitivity
- 10cm length, Finesse ~ 850000
- FS mirrors for thermal noise $<10^{-15}$
- Heavy passive thermal shielding (τ > 4 days)

J. Millo et al., Phys. Rev. A 79, 053829 (2009)
S. Dawkins et al. Appl. Phys. B 99, 41 (2010)
J.J. McFerran et al., Opt. Lett. 37, 3477 (2012)

- ➔ Flicker floor ~4×10^{-16} each
- ➔ Linewidth ~170mHz
- ➔ ~-20 mHz/s drift (-7×10^{-17}/s)
- ➔ Months continuous operation



The benefits from practice



Black :

- 2 horizontal cavities
- ULE mirrors @ 1.55 µm

~2×10^{-15} @ 1s

Red :

- Horizontal vs 1 Vertical
- Fused Silica

mirrors@1.06 µm

(low thermal noise)

results : ~8×10^{-16} @ 1s
~7×10^{-16} @ 4s

plus celle de Bérengère ?

Ultra-stable laser for REFIMEVE

Operational ultra-stable laser : provided by REFIMEVE

- Expected stability @1s : $<10^{-15}$
- Expected drift : <10 Hz/s
- set-up in operational room
- Construction 2 semester 2013
- Design by Jérome Lodewyck, Rodolphe Le Targat
- Signal feeding 1st semester

Improvements :

- Auto-relock ?
- Error detection, supervision ??
- Correction of the drift vs H-Maser

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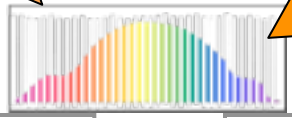

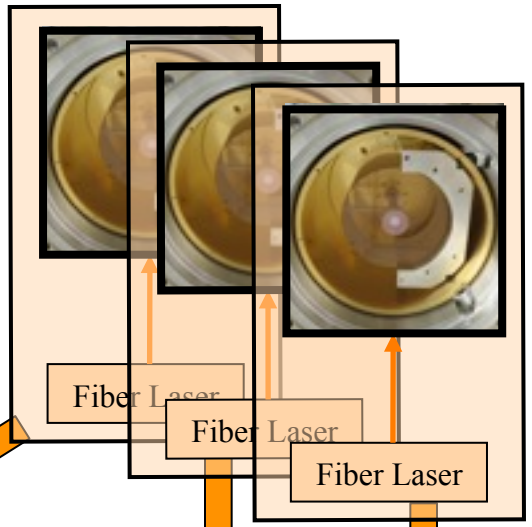

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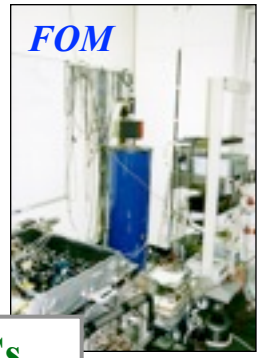

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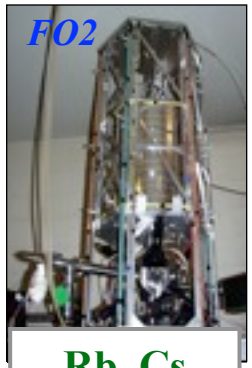

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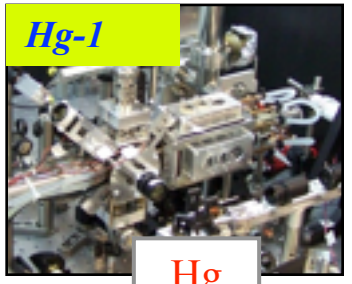

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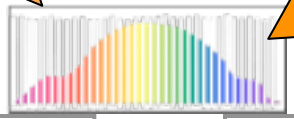

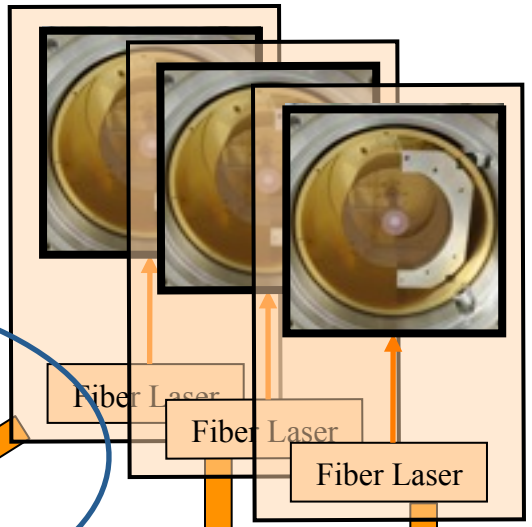

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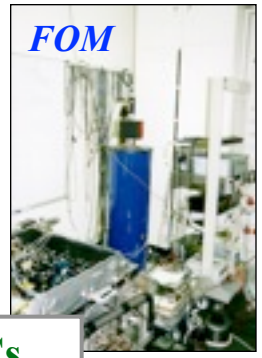

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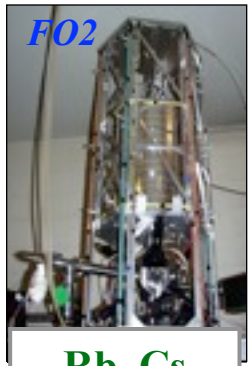

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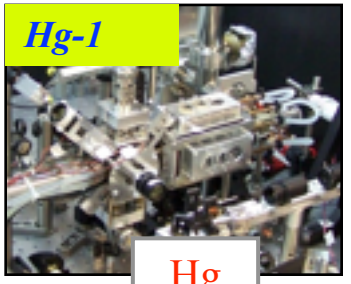
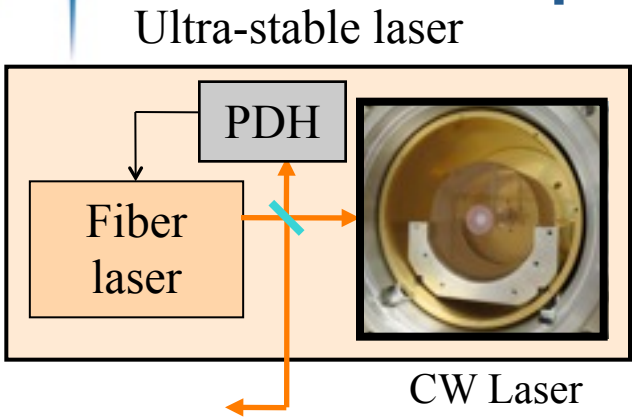


Hg

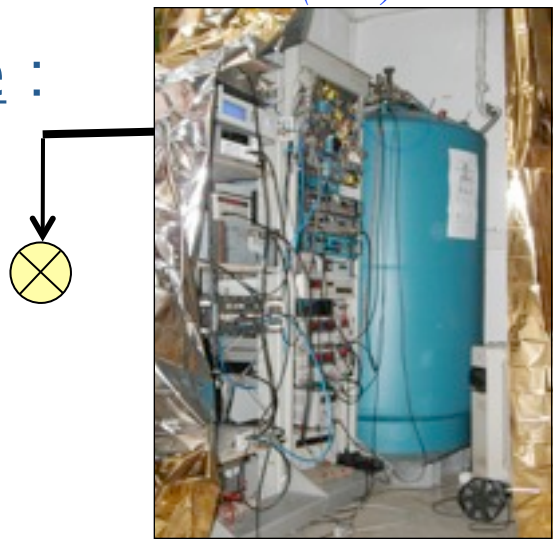
Optical to Microwave gap

REFIMEVE provide one dedicated operational frequency comb



Cryogenic Saphir Oscillator (CSO).

Expert at Syrte :
Yann Le Coq



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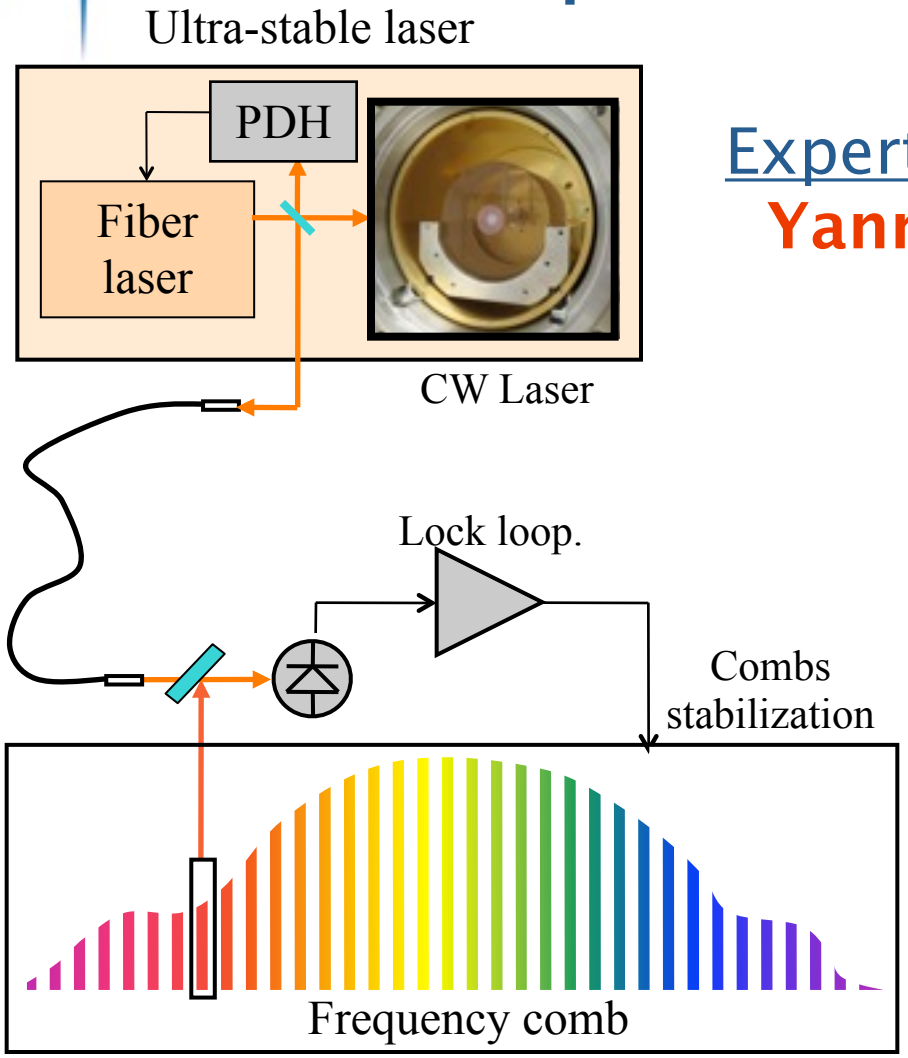

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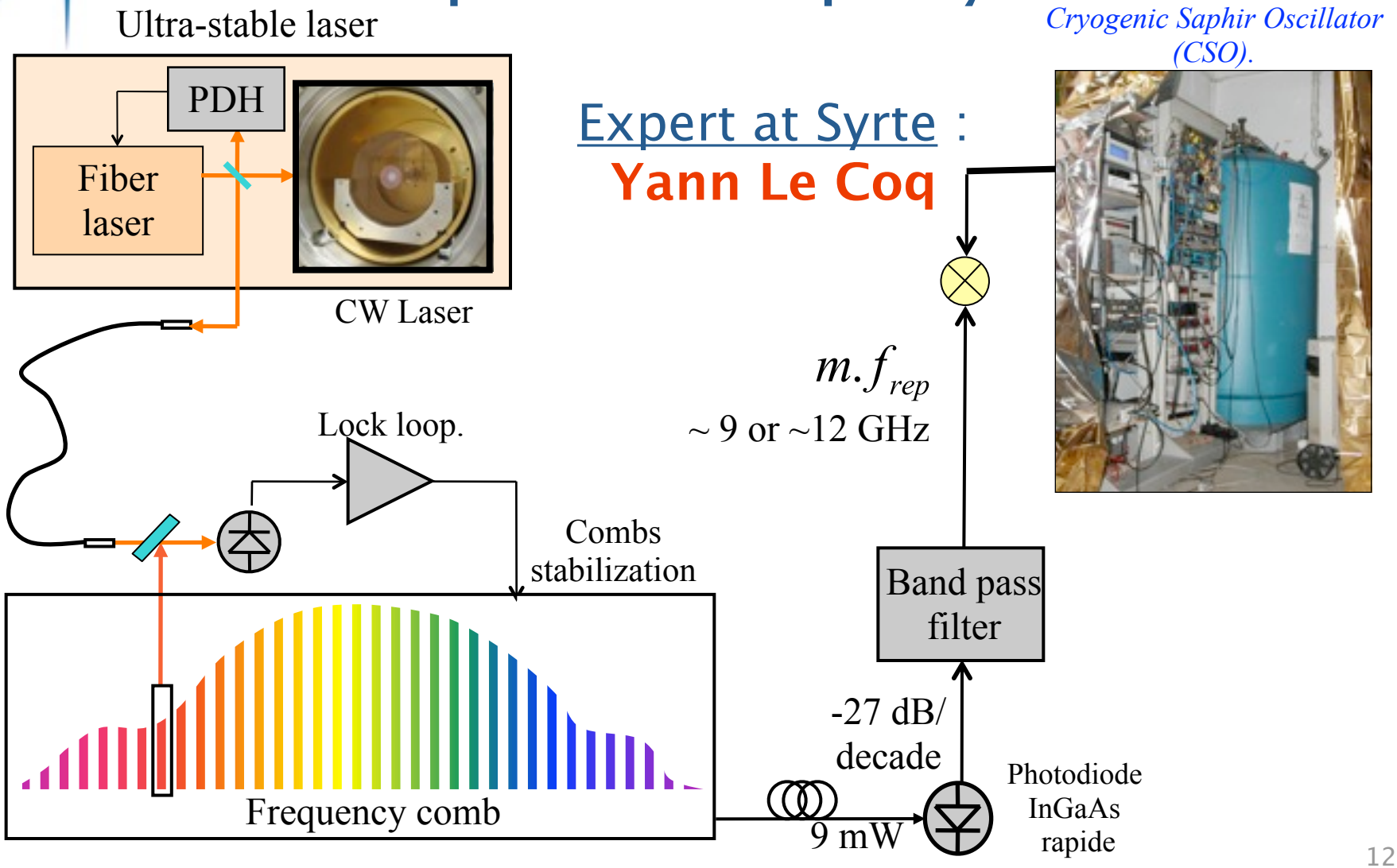

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Ultra-stable laser

PDH

Fiber laser

CW Laser

Lock loop.

Combs stabilization

Frequency comb

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$m.f_{rep}$

~ 9 or ~12 GHz

Band pass filter

9 mW

Photodiode InGaAs rapide

About your User comb :
See presentation by Anne Amy Klein this afternoon

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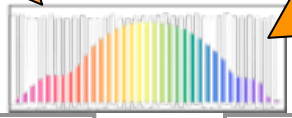

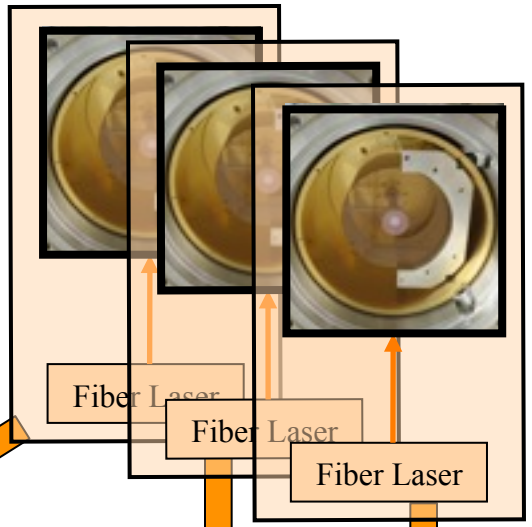

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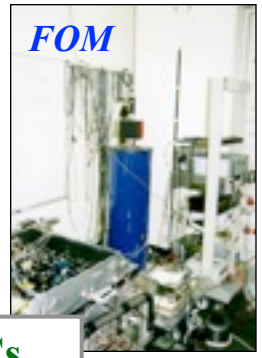

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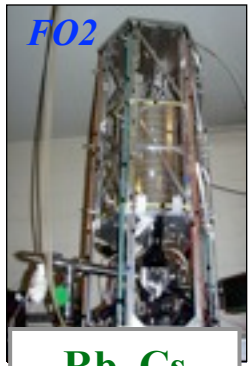

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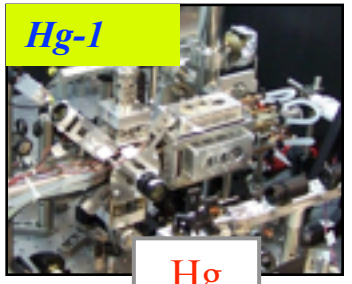

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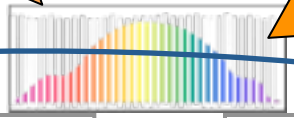
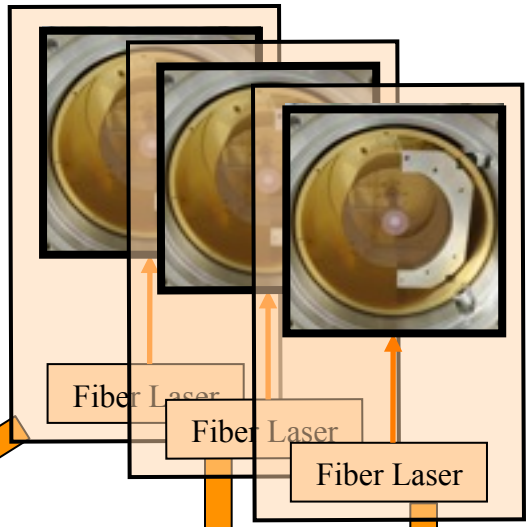
+1 GHz distribution

Frequency comb

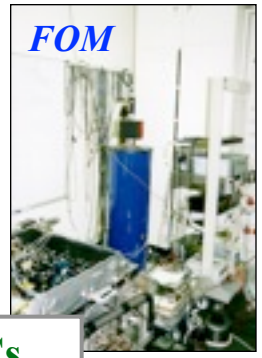


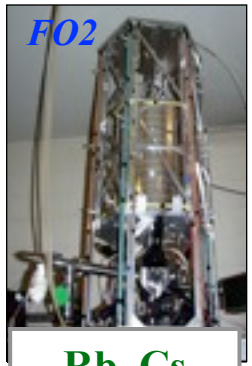


Ultra-stable Lasers

Atoms

Atomic fountains



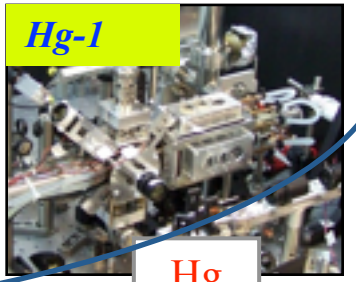


Cs

Rb, Cs

Optical lattice clocks

Sr



Hg

Accuracy

Accuracy : Level of credibility of a measurement

- Uncertainty budget
- Standards comparison campaigns

Atomic fountains : H-maser vs FOx

Ultimate accuracy : a few 10^{-16}

Operational almost continuously

Contributions to TAI

PHARAO/ACES

Sr lattice clock

Ultimate accuracy few 10^{-17}

Heavy research programs

Contributor	Correction (10^{-16})	Uncertainty (10^{-16})
Lattice Stark (scalar/tensor)	−6.5	0.5
Hyperpolarizability (lattice)	−0.2	0.2
BBR Stark	52.1	1.0
ac Stark (probe)	0.2	0.1
First-order Zeeman	0.2	0.2
Second-order Zeeman	0.2	0.02
Density	8.9	0.8
Line pulling	0	0.2
Servo error	0	0.5
Second-order Doppler	0	<<0.01
Systematic total	54.9	1.5

A. Ludlow et al. Science, 319, 1805 (2008)

No 'real-time' accuracy !

What will be sent ?

1.542 nm CW laser light,

ultra-stable, dedrifted vs 1 GHz CSO

But :

No warranty

for 24/7 operation.

Typical performances:

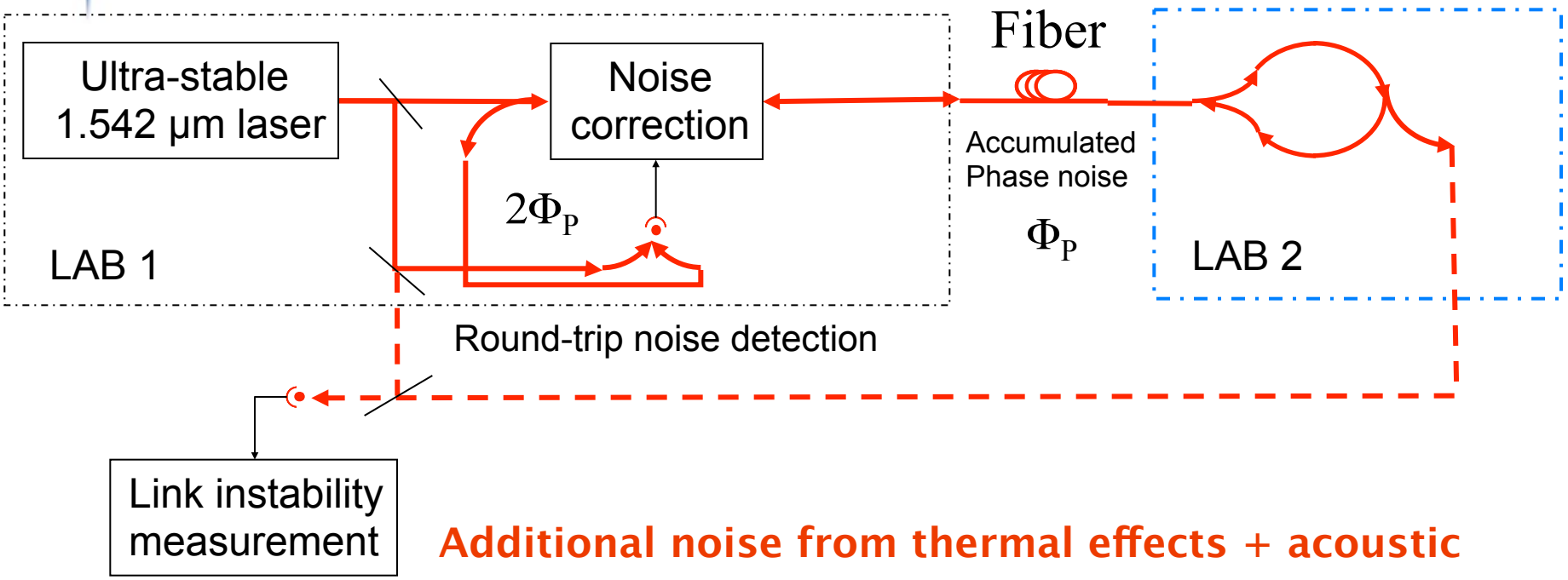
$<10^{-15}$ @1s-1 000s

a few 10^{-14} accuracy

Top-level Accuracy for specific experiments

Please, schedule it with SYRTE !

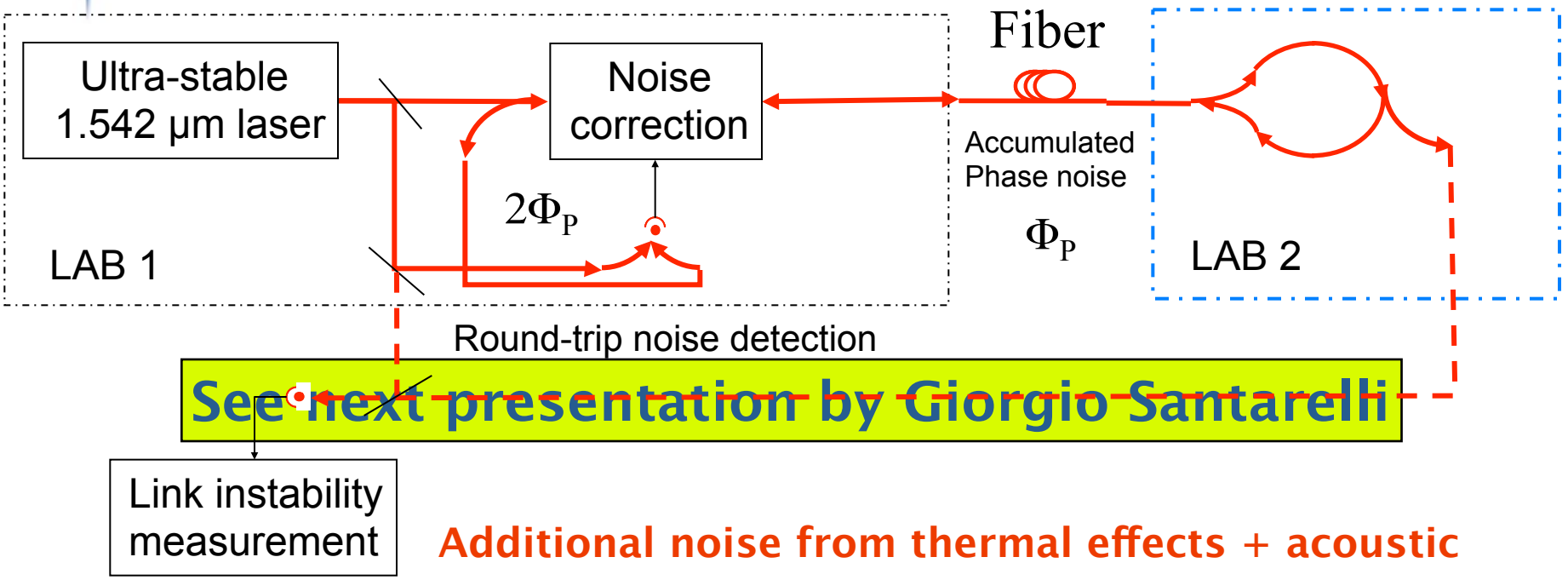
What will you receive ?



Additional noise from thermal effects + acoustic

- Noise correction Bandwidh limited
  More Noise
- Losses
  Less Signal
- Active compensation

What will you receive ?



Additional noise from thermal effects + acoustic

- Noise correction Bandwidh limited
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  Less Signal
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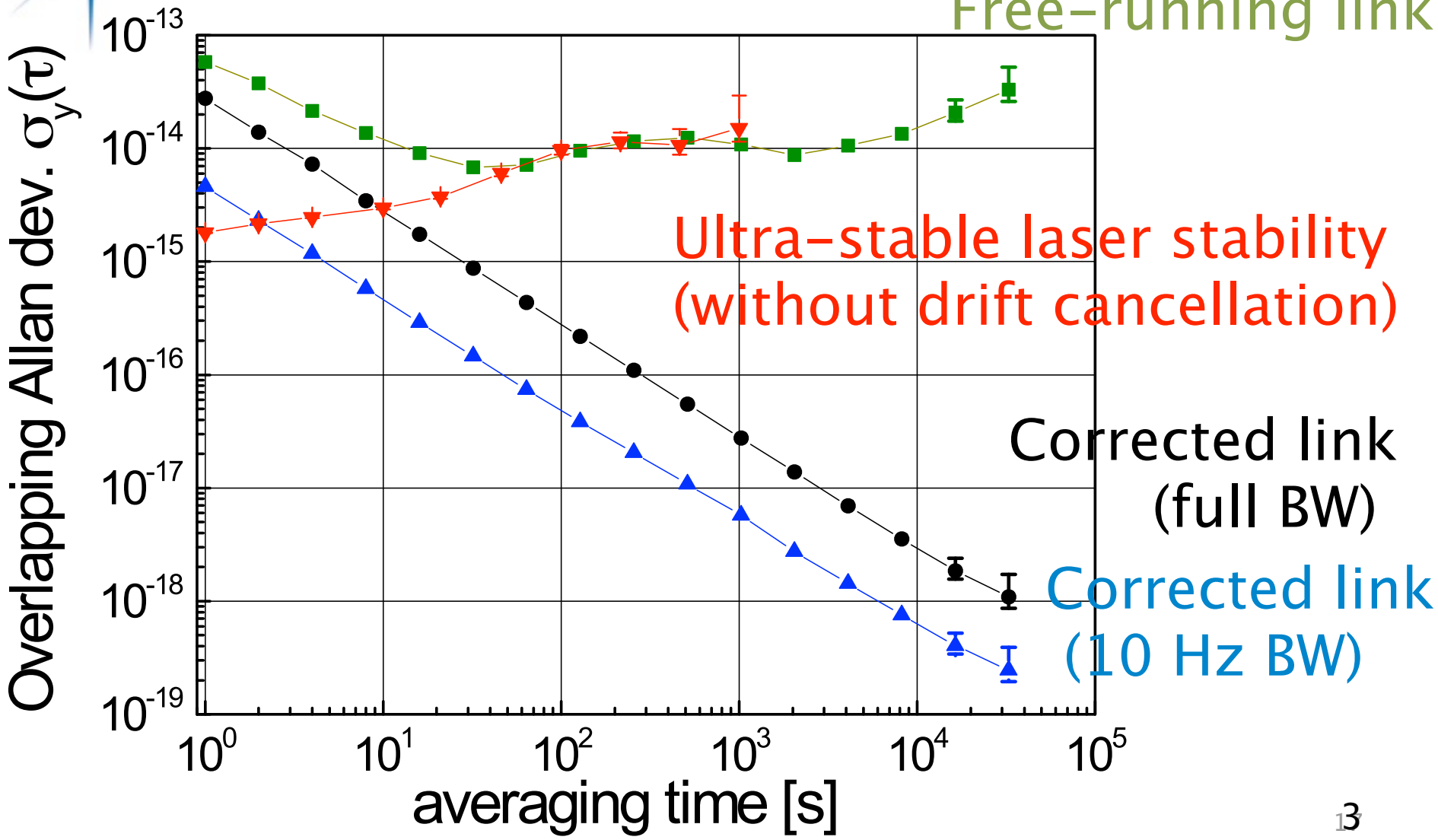
Link frequency stability after 540-km



Outlook

- Research and development
  - No warranty neither for the optical link !
    - Supervision of the network
  - Paris-Strasbourg as test bed, connection to PTB
  - Next goal : Toulouse
- Improvement of reliability and performances with time
  - H-maser steering
  - Alternate possibility under development: ultra stable laser (No LHe) + femtosecond optical
    - $<3\times10^{-15}$ @ 1s: Appl. Phys. Lett. 94, 141105 (2009)
    - Also at PTB: Phys. Rev. A 79, 031803 (2009)
  - Ultra low noise optical to microwave conversion: 10^{-16} @1s, sub 100 attosecond residual timing jitter

    W. Zhang et al., Appl. Phys. Lett. 96, 211105 (2010)
- Time transfer

Acknowledgements

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Microwave frequency group
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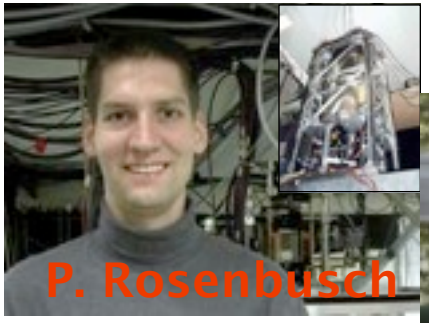

Thank you for attention !

Questions ?